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Siri Mo

Abstract

As the Norwegian public road industry is characterized as a "low uncertainty" industry, especially in comparison to the Norwegian oil and gas industry, it has been common to give more weight to the economic perspective in decision-making processes in road safety work. The use of cost-benefit analyses in particular, which in its earliest form was created and used to ascertain how much society is willing to pay in order to gain a certain benefit, is still prevalent in present day priority setting and policy development in road safety. Such practices are justified by reference to portfolio theory, a strictly economic strategy of calculating project worth. Which road safety measures are chosen for implementation depends to a large extent on how large the expected benefits associated with the implementation are, compared to how much the implementation is expected to cost. A problem that arises with this strategy is that expected values are subject to uncertainty and variation, associated with the assumptions and knowledge of the analyst that performs the calculation. Issues may arise if road safety measures are ranked solely based on these assessments of expected values, with no consideration to the strength of knowledge used to calculate them.

The Handbook of Road Safety Measures by (Elvik, Vaa, Hoye, & Sorensen, 2009) features a collection of 128 different road safety measures, each assessed with respect to costs and benefits related to the effect of their implementation. Although the authors of the book claim that its contents are not designed for direct use in road safety policy making or decisions on how to prioritize between different safety measures, cost-benefit analyses such as those presented in the book lie at the core of actual policy making in the Norwegian Public Road Administration (NPRA). This thesis suggests that with the addition of some considerations on the uncertainty inherent in the calculations of the cost-benefit analyses, which are based on expected values and subjective assessments, the authors are able to present deeper and more insightful results than those found in the current edition of their work. An illustrative example which illustrates the benefits of such considerations based on assessments found in *The Handbook of Road Safety Measures* (Elvik et al., 2009) is presented. How uncertainty considerations may be included in future editions of the book is discussed.

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List of abbreviations

AADT	Annual Average Daily Traffic
C	Consequence
NOK	Norwegian Kroner
NPRA	Norwegian Public Roads Administration
NPV	Net Present Value
P	Probability
SoK	Strength of Knowledge
SPUI	Single-Point Urban Interchange
TUDI	Tight Urban Diamond Interchange

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Chapter 1 - Introduction

1.1 - Background for thesis problem

Due to its status as a comparatively "low uncertainty" industry, safety work in the Norwegian traffic industry is usually performed with heavy emphasis on the economic perspective. Assessment methods such as cost-benefit and cost-effectiveness analyses are popular tools used for comparing and ranking possible projects. These are methods found in *The Handbook of Road Safety Measures* (Elvik et al., 2009). Each safety measure is investigated with respect to their effect on accident rates on the road, as well as their effect on driver mobility and surrounding environment. Factors such as reduced accident rates and reduction in vehicle travel time are counted amongst the benefits of implementing the measure, while money spent on implementing and maintaining the measure amount to expected costs.

The motivation and rationale behind using cost-benefit analyses as decision-making basis for public roads work is sound. The responsibility of planning, building and maintaining public roads rests on the government entity known as the Norwegian Public Road Administration (Statens vegvesen, 2018b), who are a public entity dealing with public issues, and are subsequently working with limited funds. Gaining the greatest amount of benefits for what available resources there are should be and is a powerful motivator. Contesting the basic principles of cost-benefit analysis is not within the scope of this thesis. The subject of interest for this thesis is the reliability of the cost-benefit analyses, judged by the information used to create them. In order to make an informed decision about which project to choose, particularly for projects which appear similar in quality based on cost-benefit analyses alone, it is useful to look further into the information used to support the analyst's results and subsequent judgements on the analyzed safety measures.

The thesis uses analysis work found in *The Handbook of Road Safety Measures* (Elvik et al., 2009) in order to showcase how sole reliance on cost-benefit analyses in the Norwegian public road industry may provide the decision-makers with inadequate support for informed decision-making. When the main component of the analysis is the use of expected values, there is a need for additional insights into how the results become what they become. A reasonable assessment of the subjective knowledge basis used in the analysis should be provided, in order to understand further what makes the analyst claim what they claim. The analyses found in *The Handbook of Road Safety Measures* (Elvik et al., 2009) provide much information gathered from various sources, but there is no dedicated assessment of how the sources affect the authors' strength of knowledge. As such, there is no indication on the level of certainty with which the results of the safety measure assessments are presented.

1.2 - Thesis objective

The objective of this thesis is an attempt to include more considerations on uncertainty in cost-benefit analyses conducted in *The Handbook of Road Safety Measures* (Elvik et al., 2009), which presently mainly focuses on whether the costs of implementing a safety measure is countered by the benefits. A supplement of knowledge assessment is suggested for the presentation of the results of these analyses. Discussion on sole focus on the economic considerations of the road safety problem is provided and linked to findings from the main part of the thesis.

1.3 - Limitations

As the contents of the thesis is based solely around the book *The Handbook of Road Safety Measures* (Elvik et al., 2009), the work associated with this thesis is intended to provide a contribution to public road safety work in Norway, and is therefore based on documented challenges and problems on Norwegian roads. The thesis limits itself to information gathered from the book, and how this is presented to the reader.

1.4 - Methodology

The work done in this thesis is primarily qualitative and comparative in nature. After a literature study, where information and theoretical literature associated with the topic of the thesis is presented, analyses of some chosen sections found in *The Handbook of Road Safety Measures* (Elvik et al., 2009) with respect to its use of knowledge gained from literature studies are presented. Although the assessed sections from the book contains numerical figures, assessment of these is not the focus of the thesis. The thesis demonstrates and discusses the importance of qualitative assessment of knowledge in analyses which depend on expected values using subjective probabilities, by performing such assessments for knowledge presented in *The Handbook of Road Safety Measures* (Elvik et al., 2009).

1.5 - Structure of thesis

The thesis is structured in a hierarchy of chapters, sections and sub-sections. The chapters are the main parts of the thesis, and serve as the inner core of the structure. The sections cover the various topics in each chapter, and the sub-sections elaborate on specific details within each topic. This first chapter serves as the introduction to the thesis itself, and sets up its main points. The second chapter discusses literature relevant to the topics discussed later in the thesis. The third chapter is the main contribution of the thesis, an illustrative example of how assessment of background knowledge may supplement the analyses conducted in *The Handbook of Road Safety Measures* (Elvik et al., 2009), and a suggestion as to how to include such knowledge assessments as a part of the road safety measure assessments done in the book. The fourth chapter provides discussion on the topic of sole focus on expected values in risk and safety contexts, as well as on the importance of maintaining consistency and transparency in analyses which aim to provide input for comparative decision-making. Finally, a conclusion is reached in chapter 5, where a short summary of the most important findings of the thesis is provided. A list of references used in the thesis, as well as in the presented sections in *The Handbook of Road Safety Measures* (Elvik et al., 2009), is included at the very end of the thesis.

Chapter 2 - Theoretical background

In order to make an informed decision relating to a problem, activity or situation, there is a need for analyses and assessments of relevant aspects of the problem. Decisions are made every day, in contexts ranging in significance from the absolutely mundane to the life-or-death important. Many different aspects are available for shaping the process of making decisions in the contexts they arise in. As the context of the decision-making process grows in both significance and complexity, it is obvious that more input is necessary to make an informed decision. It can hardly be contested that assessment of a project's profitability is essential for achieving optimal use of available resources. The economic perspective largely revolves around monetary values of operations, and it is not uncommon to rely heavily on expected values with respect to decision-making. Projects which have the potential to give high returns are chosen over those with lower expected yield. It is this perspective which is the focus of the analyses conducted in *The Handbook of Road Safety Measures* (Elvik et al., 2009). Various aspects connected to such an approach to the traffic safety problem are presented in this chapter.

2.1 - The basics

2.1.1 - Risk definition and description

The Handbook of Road Safety Measures (Elvik et al., 2009) assesses and lists safety measures for the improvement of road safety and risk reduction. In order to fully understand the problem and consequences of risks on the road, as well as in other real life situations, there is a need for a solid definition and description of risk as a concept. The definition of the risk concept which is used in following sections of this thesis describes risk as a combination of consequences (C) of an activity, and the uncertainty (U) related to them (Aven, 2015). It is also possible to split the consequence component into initiating events (A) and the consequences (C) that follow, though the notations (C,U) and (A,C,U) are equivalent. Imagine, for illustrative purposes, that an off-road accident on a rural road occurs. This accident is denoted as per the risk definition above as the initiating event (A). After this event happens, there are several possible outcomes, or consequences (C); severe injuries, fatalities, damage of road furniture, etc. The uncertainty (U) in this example manifests as the risk assessor's inability to know what the consequences of the accident are before the accident has occurred. The two main components of risk has thus been identified, and the risk concept has been defined.

A mere definition of risk as a concept is however not sufficient for risk assessment or management. There is a need to measure and define the risk. A risk description is obtained by specification of the consequences, and by use of a descriptor (measure) of the uncertainty (Aven, 2015). In practise, this means that certain set of quantities of interest that characterize the consequences (C') are identified, and measured by way of assigned probabilities. Continuing with the example above, the quantities of interest could be for example number of fatalities or severe injuries as a result of the off-road accident, and the descriptor of uncertainty could be probabilities obtained from historical accident data. It could be discovered, for example, that the probability (P) of dying as a result of an off-road accident on a rural road is 9%. It is also possible to further assess the strength of the knowledge (K) upon which this probability (P) is based. In summation, the following is arrived at:

Risk concept = (C,U)
Risk description = (C', Q, K)

C = consequences
U = uncertainty
C' = set of quantities that characterize C
Q = measure of uncertainty (probability)
K = background knowledge (data, expert statements, information, etc.)

2.1.2 - Expected values

The calculation and evaluation of expected values lies at the centre of the safety measure analyses in *The Handbook of Road Safety Measures* (Elvik et al., 2009). Expected values are usually values which are calculated aggregates of various data points. In situations where several outcomes are possible, and there are several values that the unknown quantity may assume, an expected value weighs the various outcomes (consequences) against the probability of the outcome:

$$E[X] = \sum_{i=1}^{n} (p_1 * C_1) + (p_2 * C_2) + \cdots + (p_n * C_n)$$

... where X is the unknown quantity of a certain description, such as number of fatalities in a traffic accident, n is the number of identified consequences, and p_i is the probability that consequence C_i occurs. For example, for an initiating event A such as a collision on the highway, expected values for consequences such as number of fatalities may be calculated. If the possible outcomes of such a collision are 0, 1, 2 and 4 fatalities, with probabilities of 0.30, 0.56, 0.48 and 0.02 respectively, then the expected number of fatalities may be calculated to:

$$E[X] = (0.3 * 0) + (0.56 * 1) + (0.48 * 2) + (0.02 * 4) = 1.6$$

Expected values can in cases where each outcome is equally likely express an average value. However, in the example above, a value for expected number of fatalities is obtained from outcomes with different likelihoods. This value does not express an average, but is interpreted as the centre of gravity of the probability distribution of the variable X, in other words, the value of the unknown quantity which is expected from the event (Aven, 2015). Subjectively assigned probabilities are more commonly used in the calculation of expected values, as elaborated upon in later sections of the thesis.

2.1.3 - Probability

The use of probabilities in order to express uncertainty, or, the likelihood of the occurrence of an event, is a central pillar in the world of statistics and risk. The probability concept is commonly understood as a quantification of the "chance" that an uncertain event happens. Such an event could be the occurrence of slippery driving conditions on the highway, which could be quantified by the probability 15%. There are many ways of explaining and defining the probability concept, all of which yield different interpretations. As the use of probabilities stands central in calculating expected values, which comprise most of the cost-benefit analyses in *The Handbook of Road Safety Measures* (Elvik et al., 2009), it is important to have a firm grasp on what is expressed with their use. As seen in the previous sub-section of the thesis, expected values express different things depending on likelihoods of outcomes. Therefore, a selection of the most commonly used definitions are detailed and presented, supplemented by examples where applicable.

Classical probability

The classical interpretation of probability only applies in situations where there is a finite number of outcomes which are equally likely to occur. It states that the probability of some event A is given by the ratio between the number of outcomes which result in event A, and the total number of outcomes. Mathematically speaking (Aven, 2017):

$$P(A) = \frac{Number\ of\ outcomes\ resulting\ in\ event\ A}{Total\ number\ of\ outcomes} = \frac{n_A}{N}$$

The simplest illustration of this probability interpretation is presented by a roll of a die. The probability of rolling a 4 is one over six, which is 16.7%. The die is only rolled once, meaning that out of the total number of possible outcomes (6), only one of them will yield the desired outcome. The calculation becomes: P(4) = 1/6 = 0.167. Assuming the die is fair, each outcome is equally likely. It is this assumption which is critical for understanding the rationale of this probability interpretation. In practise however, there are very few situations which may be described by the rigid structure set by this probability interpretation. In fact, very few situations in real life has a finite number of outcomes which are equally likely to happen, meaning that this interpretation is hardly applicable beyond sampling and gambling situations (Aven & Reniers, 2013). Imagine that an analyst's task is to investigate the probability of a critical brake failure while driving. As such an event could have more than one cause (for example highly individual factors such as brake maintenance or varying quality of brake part manufacture), there is an unknown number of possible outcomes, as well as varying probability that each cause results in a critical brake failure. A lack of a finite number of outcomes that result in the critical brake failure, coupled with an inability to justify a statement of equal likelihood between the outcomes, renders the use of the classical probability interpretation unsuitable for road safety work.

Frequentist probability

Frequentist probabilities are presented in hypothetical experiments where the considered situation is repeated an infinite amount of times. The frequentist probability of event A transpiring in the situation is then defined as the fraction of times the event happens out of the infinite repeats of the situation (Aven & Reniers, 2013). The concept is based on the law of large numbers, which states that the fraction n_A/n converges towards a limit under certain conditions, and tacitly assumes that this limit exists. Where n_A is the amount of times event A transpires and n is the amount of repeated experiments, the frequentist probability of event A is mathematically expressed as:

$$p = P_f(A) = \lim_{n \to \infty} \frac{n_A}{n}$$

Continuing the use of the die example, if a single die is thrown an infinite amount of times under similar circumstances, the average result of the die throws will approach the expected value of the die, which is:

$$E(X) = \frac{1}{6} * (1 + 2 + 3 + 4 + 5 + 6) = \frac{21}{6} = 3{,}5$$

The real-world applicability of frequentist probabilities remains contested by experts. For example, a frequentist probability "is applicable to only those situations for which we can conceive of a repeatable experiment" (Singpurwalla, 2006). In reality, there are many situations that will not repeat themselves in such a way that frequentist probabilities are sensible to use in the first place. The rise of sea level over the next 20 years, the innocence or guilt of an accused individual, and the possible occurrence of a disease in a specific individual with a certain medical history are all examples of such situations (Aven & Reniers, 2013). A frequentist probability is a model concept, and must therefore be estimated rather than calculated.

Subjective (knowledge-based) probability

A subjective probability is an expression of the assessor's degree of belief that a certain event A will transpire. As the name implies, the assessment of a situation is highly individualized and subject to the assessor's own value judgements, which in turn is based on their own experiences and knowledge. A subjective probability is different from a frequentist probability in that it is not an estimated quantity which aims to approach some "true" unknown value, it is an assigned quantity which relies on the assessor's personal beliefs. Subjective probability is best illustrated by comparison to an urn experiment: an urn contains ten balls, one of which is blue, nine of which are red. If an assessor assigns a subjective probability of an event A to 0.1, it means that they are comparing their degree of belief or uncertainty of the event to the probability of drawing the blue ball from the urn (Aven, 2015). Assigning a knowledge-based probability to a certain outcome is the most commonly used way of expressing uncertainty, or the degree of belief the assessor harbours that the outcome will happen. In this regard, it is not common to discuss "uncertainty" within subjective probabilities, as the uncertainty is described by the assigned probability itself. As mentioned by (Aven, 2014), a more preferred point of discussion is the imprecision in the assignment. This relates in particular to the difficulty of working with very small numbers; how does one for example distinguish between assignments to the degree of 10^{-5} and 10^{-6}?

Several important points are made by (Aven & Reniers, 2013) on the nature of subjective probabilities. Despite the classical approach of describing what a subjective probability is, the urn comparison, these probabilities are not at all objective. No interpretation of subjective probabilities allows for this, as they are always used to express an assessor's degree of belief, or uncertainty, in relation to occurrences of outcomes in whatever situation is being assessed. No reference to an underlying "true" value for the probabilities are made. The assigned probabilities are however based on the background knowledge (models, assumptions, data, etc.) of the assessor, which may be strong or weak. As pointed out by (Aven & Reniers, 2013), this may raise questions about the value of the information provided by such subjective probability assignments. It then follows that subjective probability assignments should be viewed in relation to the background knowledge which produced them. Issues like these incentivises research into alternative probability assignment approaches, such as confidence intervals or imprecise probabilities, as discussed below.

Imprecise (interval) probabilities

Imprecise (interval) probabilities are subjective probabilities which are interpreted in an interval setting. For example, an assessor's assignment of a probability of 0.4 can be interpreted as the imprecision interval [0.36, 0.44], as any number in this interval is written as 0.4 when only using one digit. Referring to the urn comparison for subjective probabilities, this assignment is actually the assessor's degree of belief that the probability is larger than the probability of drawing a red ball from an urn which contains 100 balls, 36 of which are red, and smaller than the probability of drawing a red ball from the urn if 44 of the 100 balls were red. The assessor does not make any further judgements than this (Aven & Reniers, 2013). Another interpretation of imprecise (interval) probabilities is to compare the probability 0.36 to the maximum price one is willing to pay to enter into a bet in which one wins 1 if event A happens, and 0 if event A does not happen. The probability 0.44 is then the minimum price one is willing to sell the bet to another for (Aven, 2011; Walley, 1991). The latter interpretation is not applicable for reliability or risk assessment purposes, as it mixes uncertainty assessments and value judgements (Aven & Reniers, 2013).

There appears to be disagreement among the experts in regards to imprecise probabilities and their use in practical contexts. Some authors take issue with added unnecessary complexity of systems once probability intervals are introduced. Simplicity is to be preferred over complexity, as it were. (Lindley, 2013) argues that one risks to confuse the concept of interpreting a probability with the practice of measurement procedures, if imprecise probabilities are used. (Bernardo & Smith, 2009) argue that if imprecise probabilities were incorporated into the axiom system of risk and reliability, it would represent "an unnecessary confusion of the prescriptive and the descriptive". They write (Bernardo & Smith, 2009):

> *"We formulate the theory on the prescriptive assumption that we aspire to exact measurement [...], whilst acknowledging that, in practice, we have to make do with the best level of precision currently available (or devote some resources to improving our measuring instruments!)."*

Other authors take more positive stances on the use of imprecise probabilities. It is argued by (Aven, 2010) that such probabilities may in some cases contribute to precise probabilities in a supplementary fashion. It is stressed that their usefulness will depend on the context of the probabilistic analysis; if the purpose of the analysis is to express an assessor's subjective judgements based on their specific background knowledge, the logical approach would be precise probabilities. However, if the analysis seeks to provide a more "inter-subjective" knowledge description of unknown quantities targeted by the analysis, the use of imprecise probabilities may provide additional information next to precise probabilities (Aven, 2010). It is concluded by (Aven & Reniers, 2013) that more research on how to use this probability type in practical settings is required.

2.1.4 - Uncertainty (strength of knowledge)

As background knowledge will vary greatly from scenario to scenario, there is a need for a general framework of assessing its strength. Such a framework has been suggested by (Flage & Aven, 2009) and is presented below. Knowledge is here divided into three tiers; weak, medium and strong. In regards to describing significant uncertainty in relation to the available background knowledge, the authors highlight the following characteristics:

- The phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions.
- The assumptions made represent strong simplifications.
- Data are not available, or are unreliable.
- There is a lack of agreement/consensus among experts.

The knowledge is considered weak if one or more of these descriptors are applicable. Similarly, a scenario where the uncertainty about the background knowledge is considered minor or negligible, i.e. the background knowledge is able to provide a strong basis for decision-support, is described by the following:

- The phenomena involved are well understood; the models used are known to give predictions with required accuracy.
- Assumptions made are seen as very reasonable.
- Much reliable data are available.
- There is broad agreement among experts.

The knowledge can be considered strong if all the characteristics apply. Knowledge which can be described by a mixture of points from both lists is considered medium. Strength of knowledge is important to consider, especially when, as in most cases, subjective probabilities are used. It is entirely possible for an analyst to assign the same probability for an outcome, in different situations using entirely different knowledge bases. Imagine that an analyst is hired to investigate the likelihood for the event of a pedestrian to get run over by a vehicle while crossing the road at night. The analyst collects data, and forms their analysis on the assumptions that the pedestrian looks both ways before crossing, wears a retro-reflective gear in order to get noticed by traffic in the dark, and crosses at a brisk pace once the coast is clear. The analyst considers these assumptions reasonable, and assigns the probability of 0.001 to the event. What this means in reality, is that when a pedestrian fulfils all the assumptions of the analyst, then the probability assigned for the event will be relevant for the pedestrian. If that is the case, the analyst has strong background knowledge and can with confidence support their assignment of the probability that pedestrian gets run over. However, if the pedestrian does not act according to the assumptions, if for example they do not look both ways or wear retro-reflective gear, the background knowledge is no longer strong for this individual, and the assignment of 0.001 is less applicable. This vital difference in possession of information (or lack thereof) is not reflected in the output of the subjective assessment, the singular probability number. It is therefore necessary to discuss the knowledge upon which subjective probabilities and analyses are based.

2.2 - Decision-making

2.2.1 - Cost-benefit analysis

A widely used method of ascertaining a project's profitability, and thus whether or not the project should be accepted or rejected, is the cost-benefit analysis. This method utilizes expected values to estimate costs and benefits related to the project, and determines whether the project is expected to be profitable. This analysis method is the most prevalent assessment found in *The Handbook of Road Safety Measures* (Elvik et al., 2009). The method is particularly popular in economics, where possible investment opportunities and projects are assessed and ranked based on their expected net present values (E. B. Abrahamsen, Asche, & Aven, 2011):

$$E[NPV] = -I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$

... where I_0 is the cost of investing in the project, C_t is the cash flow obtained at time *t*, T is the total project lifetime, and r is the discount rate of the project. Cost-benefit analyses are very beneficial in that an assessor is able to gain an impression of the project's profitability over a longer period of time. Calculating the expected net present value of the implementation of a safety measure will for example reveal its expected monetary effectiveness over several years. When used in traffic safety work, expected values for costs and benefits are calculated for various possible projects, and the results are compared in order to make decisions on where money should be invested. A simpler way of expressing the calculation is:

$$E[NPV] = E[X] - E[C]$$

... where E[X] is expected benefits, and E[C] is expected costs. It is vital that for cost-benefit analyses that all factors are translated into equal terms of measurement, money, in order to maintain consistency and transparency in the decision-making process, as concluded by an article by (E. B. Abrahamsen et al., 2011). Arguments are raised about how the necessity of applying manual interpretation of and assumptions on non-economic variables present in the context of the analysis, and how this leads to a high degree of arbitrariness. The ethical side of converting non-market goods such as human lives into monetary terms is also a point of contention for many experts.

2.2.2 - Portfolio theory

The liberal use of economic analyses as decision-making basis is often justified by reference to the portfolio theory. A portfolio is in this case a collection of projects, for example implementation of a certain road safety measure on N roads. Assuming that each project within the portfolio is weighted at 1/N, and granting the expectation and variance of individual project returns r_i the expressions $E_i = E(r_i)$ and $VAR_i = VAR(r_i)$, the following mathematical expressions are derived (E. Abrahamsen, Aven, Vinnem, & Wiencke, 2004):

$$E_p = \sum_{i=1}^{N} \frac{1}{N} * E_i = \frac{1}{N} \sum_{i=1}^{N} E_i$$

... for the expectation of the portfolio, and for the variance (E. Abrahamsen et al., 2004):

$$VAR_p = \sum_{i=1}^{N} \left(\frac{1}{N}\right)^2 * VAR_i + \sum_{i=1}^{N} \sum_{j \neq i : j=1}^{N} \left(\frac{1}{N}\right)^2 * COV_{i,j}$$

$$VAR_p = \frac{1}{N} * \overline{VAR} + \left(1 - \frac{1}{N}\right) * \overline{COV}$$

$$VAR_p = unsystematic\ risk + systematic\ risk$$

... where covariance between projects *i* and *j* within the portfolio, as well as average variance and covariance is given as (E. Abrahamsen et al., 2004):

$$COV_{i,j} = E\{(r_i - E_i) * (r_j - E_j)\}$$

$$\overline{VAR} = \frac{1}{N} \sum_{i=1}^{N} VAR_i$$

$$\overline{COV} = \frac{1}{N^2 - N} * \sum_{i=1}^{N} \sum_{j \neq i : j=1}^{N} COV_{i,j}$$

As explained by E. Abrahamsen et al. (2004), the real-life value of the portfolio is equal to its calculated expected value plus risk. This risk consists of systematic and unsystematic risks, systematic risks being tied to general market movements, and unsystematic risks encompassing the specific risks in the various projects. Particularly for the equation of portfolio variance VAR_p, notice how once N grows, the term involving average project variance grows smaller and smaller. When N grows sufficiently large, portfolio variance will be approximately equal to average project covariance. The result of this is that unsystematic risks grow negligible when the number of projects grows large. This removal of economic unsystematic risks is done by the process of risk diversification into many projects. Thus, when ignoring the systematic risks in the portfolio, the total cash flow including all the projects in the portfolio is approximately equal to the expected value for all cash flows. The relationship between the actual value of the portfolio and its calculated statistical expected value is then equal to (E. Abrahamsen et al., 2004):

$$Y' = EY' + \ systematic\ risk$$

$$systematic\ risk = \ Y' - EY'$$

... where Y' is the actual value of the portfolio and EY' is its statistical expected value. As shown, the difference between expected and actual portfolio value is only dependent on systematic risk.

2.2.3 - Cost-effectiveness analysis

An alternative to the cost-benefit analysis is the cost-effectiveness analysis. This analysis method describes the ratio between expected costs and benefits, for example expected cost per expected number of fatalities prevented (Aven, 2015). This method is more versatile than the usage of cost-benefit analyses, not only because ratios are more viable for comparative purposes, but also because cost-effectiveness can be expressed by any kind of quantified expected benefit. Since there is no need to translate all attributes to monetary values, the arguably morally questionable practise of putting a monetary price on non-market goods such as human lives (E. B. Abrahamsen et al., 2011) is more or less sidestepped. If a road safety measure costs NOK 5 million to implement, and it is estimated that the installation of the measure will reduce number of expected fatalities by 20%, then the cost-effectiveness of the measure will be calculated as:

$$\frac{E[C]}{E[X]} = \frac{5.000.000\ kr}{0.2} = 25.000.000\ kr$$

... where E[C] are expected costs, and E[X] are expected benefits. This particular index is often referred to as the ICAF, or the Implied Cost of Averting a Fatality (Aven, 2015). Indices like this can be calculated and then compared to reference values, in order to determine the effectiveness of the safety measure. Safety measures can then be compared based on how cost-effective they are expected to be. In a more general sense, a project (the installation of a certain safety measure, in this case) is considered "cost effective" if it can be described as being (Petitti, 2000):

- less costly and at least as effective
- more effective and more costly, with the added benefit worth the added cost
- less effective and less costly, with the added benefit of an alternative not worth the added cost
- cost saving with an equal or better outcome

2.2.4 - Vision Zero

Vision Zero is the guiding principle used by the NPRA for their road safety efforts. In its simplest definition, it is a principle which harbours the long-time goal of reducing a specific undesirable occurrence or outcome to zero, such as number of fatalities or concentration of a hazardous substance (Aven & Selvik, 2012). In traffic safety, this means that the long-term goal of all road safety work is the reduction of number of traffic-related fatalities and serious injuries to zero. The principle is verified by criteria for rational goals, presented by (Edvardsson & Hansson, 2005):

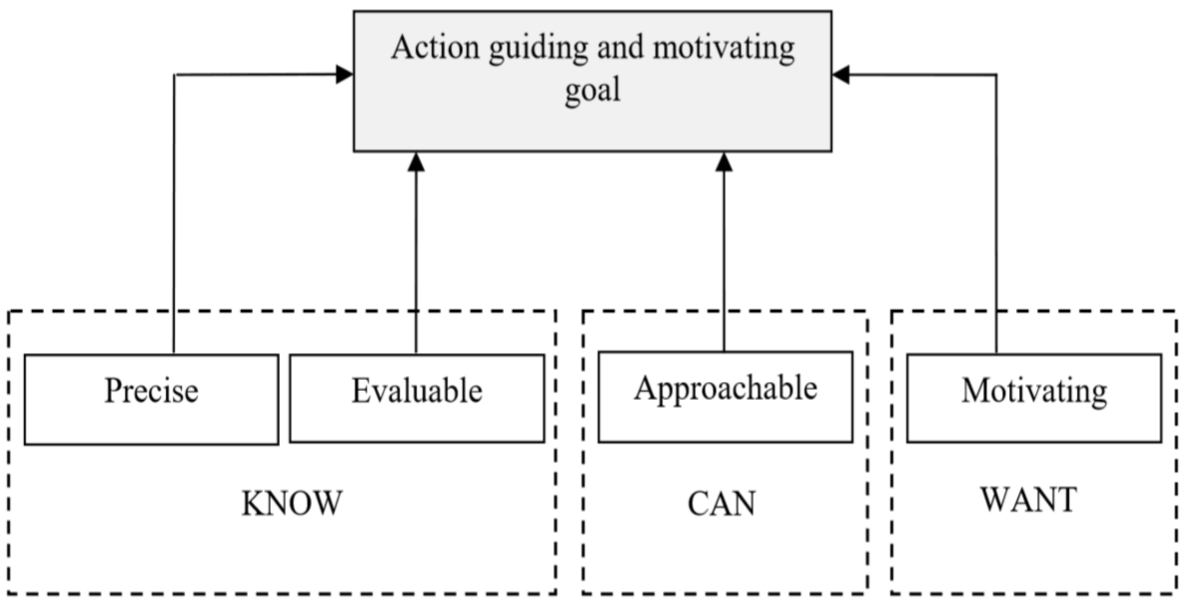


Figure 1: Criteria for rational goals (Edvardsson & Hansson, 2005)

As long as Vision Zero provides a rational goal for the decision-makers, the principle is regarded as suitable. A rational goal is one that can be characterised as being (Aven & Selvik, 2012):

- Precise:
  The goal must well defined, understandable, and clear.
- Evaluable:
  Progress towards the goal must be able to be measured.
- Approachable:
  The goal must be possible to reach, or it must be possible to work towards the goal with progress
- Motivating:
  There must be motivation from the decision-maker's side to achieve the goal, the decision-maker must be willing to make an effort in investing time and resources.

Several authors, for example Johansson (2009) and Rosencrantz, Edvardsson, and Hansson (2007), have concluded that the principle is indeed a good fit for the challenges faced in traffic safety.

2.3 - The structure of The Handbook of Road Safety Measures

The Handbook of Road Safety Measures (Elvik et al., 2009) is a massive compilation of 128 different identified road safety measures which may be implemented by the NPRA in order to reduce traffic related fatalities and injuries. Each safety measure is explored and assessed in detail, with particular focus on their expected costs and benefits. The book intends to provide answers for the following questions (Elvik et al., 2009):

- Which measures can be used to reduce the number of traffic accidents or the severity of injury in such accidents?
- Which accident problems and types of injury are affected by the different measures?
- What effects on accidents and injuries do the various road safety measures have according to international research?
- What effects to the measures have on mobility and the environment?
- What are the costs of road safety measures?
- Is it possible to make cost-benefit evaluations of the measures?
- Which measures give the greatest benefits for traffic safety seen in relation to the cost of the measures?

The book identifies traffic problems which the safety measure in question is thought to combat, the main objectives of said safety measure, its effects on accidents, mobility and the environment, as well as costs and benefits associated with implementation of the measure. Each safety measure assessment is concluded with a benefit-cost ratio, which sums up whether the implementation of the measure is expected to yield benefits greater than its costs. This structure, in addition to the last point of the intention list above, seems to indicate an underlying goal of creating a simple decision-making basis for, for example, prioritizing between the safety measures. In this respect, the book can be interpreted as a manual of sorts, an encyclopaedia on the cost-effectiveness of road safety measures. This sentiment goes against the intention of the authors of the book, however, who write the following in the introduction of the book (Elvik et al., 2009):

> *"This book is not a technical design handbook. It does not tell readers how to design a junction or how to build a car. This book does not offer a prescription for road safety policy. It does not tell readers which road safety measures ought to be taken, nor does it instruct policy makers in how to set priorities for the provision of road safety measures."*

The objective of this thesis is not to alter the structure of *The Handbook of Road Safety Measures* (Elvik et al., 2009) so that it can be used for purposes such as road safety measure prioritization. Although this is done to demonstrate its main points, the thesis mainly advocates for additional insight into the analyses performed by the assessor (the authors of the book in this case). In risk assessment work, it is of vital importance to base calculations and assessments on strong knowledge, in order to reduce the uncertainty about the outcomes as much as possible. Including the assessor's thoughts about the studies and statistics used to achieve the results listed in the book, will grant the assessments more depth. The following sub-section of the thesis presents and explains the framework of assessing various safety measures which is used in *The Handbook of Road Safety Measures* (Elvik et al., 2009). The sub-section is structured in the same manner that each safety measure is presented, with a head-line and an explanation of associated content.

2.3.1 - Problem and objective

The opening section of each safety measure assessment listed in *The Handbook of Road Safety Measures* is dedicated to an explanation of relevant traffic problems which are thought to be alleviated by implementation of the safety measure in question. As the individual goals of the safety measures differ (goals such as accident prevention, damage reduction, increase of mobility and feeling of security, etc., singularly or in conjunction with other goals), these sections vary greatly in content and elaboration. Certain traffic problems are most efficiently communicated through the use of accident data and statistics, whereas others may require more qualitative descriptions; accident risk for cyclists in traffic is easily explained using accident figures, such as a comparative study of accident frequency between cyclists and cars, while a problem such as reduced feeling of security experienced by cyclists on roads which do not accommodate them must be defined by other means.

2.3.2 - Description of the measure

This section of the framework gives a description of the characteristics and intention of the safety measure, as well as a list of different types or designs of the measure, should they exist. Illustrations are given in certain cases, where necessary for the distinction between different types or designs.

2.3.3 - Effect on accidents

This section serves as a summation of available research on the safety measure's effect on accidents, the severity of injuries caused by accidents, or both. This effect is usually expressed in percentage change in number of accidents or associated injuries which can be attributed to the safety measure. For measures for which no studies on effects on road safety exists, the effect is described in other ways. Some regard is given to statistical uncertainty in the estimates on the effects on road safety, in the form of 95% confidence intervals. In addition to these impact measures, key points found in the available studies are mentioned.

2.3.4 - Effect on mobility

Many of the listed safety measures impact the mobility of traffic in some way. This section offers a brief explanation of this effect, although not as extensively as the safety measure's effects on accidents. Both positive and negative effects are mentioned.

2.3.5 - Effect on the environment

As with the section on the safety measure's effect on mobility, a small section of the framework is dedicated to the safety measure's effect on the environment. In particular, aspects such as air pollution, noise, and intrusions on the surrounding landscape are of interest.

2.3.6 - Costs

This section presents estimates of costs which are used in the cost-benefit analysis in the following section of the framework. The following is written on the contents of this section of the framework (Elvik et al., 2009):

> "*For the majority of measures, information is given regarding the cost of the measure. The information is taken partly from research reports and partly from producers or dealers in safety equipment. Good estimates of costs have not always been found. The cost figures presented are usually an estimate of the average cost of a 'unit' of a measure, for example, 1 km of track for walking and cycling, one roundabout, one signalized junction, one seat belt, one set of ABS brakes, etc. In addition, total costs are presented for measures whose extent of usage is sufficiently well known.*"

2.3.7 - Cost-benefit analysis

For most of the safety measures, some example of cost-benefit analysis is given. Sometimes this section refers to exterior studies or analyses whose contents sufficiently cover the topic discussed. Other times, a numerical example is presented. In the introduction of the textbook, the authors urge the reader to keep in mind that the results of cost-benefit analyses are strongly dependent on the analysis context. The monetary evaluations used in the analyses presented in the book refer to the at the time current situation in Norway, which are not necessarily the same as for other countries for example (Elvik et al., 2009)

Chapter 3 - Comparing three safety measures

In this section of the thesis, three examples of safety measures listed in *The Handbook of Road Safety Measures* (Elvik et al., 2009) are presented and assessed using the framework explained in section 2.3 of the thesis. The examples used are described as they appear in the book, with no additional comments from the author of this thesis. The safety measures are described in objective and design, studies on the safety measures' effects on accidents, mobility and the environment are summarized and presented, costs associated with the installation and maintenance of the safety measures are described, and findings are summarized and discussed with respect to a cost-benefit analysis. Two of the chosen safety measures have similar benefit-cost ratios, but have cost-benefit calculations based on different strength levels of background knowledge. The third chosen safety measure has a lower benefit-cost ratio, but has calculations based on much stronger background knowledge. This section exists to showcase a possible prioritization process, and how differently the outcome can be if the assessor goes one step beyond the results of a cost-benefit analysis.

3.1 - Safety measure: guard rails and crash cushions

3.1.1 - Problem and objective

The main objective of guard rails and crash cushions is to prevent head-on collisions and off-road accidents. These measures are physical structures which are designed to, ideally, catch and direct a vehicle to a controlled halt. Vehicles that collide with a guard rail or crash cushion shall not be thrown out of control back onto the carriage way, and the installation of the measures shall not obstruct visibility or give a misleading impression of the road alignment. The installation of these measures are particularly important for the Norwegian traffic scene, as there exists many steep slopes, rocks, trees, water as well as other fixed obstacles along Norwegian roads which are likely to cause injury in case of an accident. The following accident statistics are included for the problems which these safety measures are intended to combat (Elvik et al., 2009):

- Accidents involving vehicles driving off the road makes up about 25% of injuries per accident which were reported to the police (Statistisk sentralbyrå, 2000).
- In several studies (Glennon & Tamburri, 1967; Pettersson, 1977) it has been found that single vehicle off-road accidents claimed 35% of road accident related fatalities in the year 2002 . It was found that as the steepness and elevation of the slope increases, so does the probability of getting injured or killed in such accidents.
- On class B motorways (motorways where there is no median barrier between opposite traffic lanes), head-on collisions represent about 36% of all police-reported personal injuries, as compared to only 14% on regular roads (Ranes, 1998).
- In driving off-the-road accidents where an object is struck and the type of object struck is known, the object type distribution was found to be: rocks/mountain at 28%, guardrails at 18%, lighting poles at 20%, trees at 13% and walls/buildings at 4% (Elvik, 2001b).

3.1.2 - Description of measure

Crash cushions and guard rails are erected in locations where one or more hazards infringe on a vehicle's safety zone (determined by a variety of factors, such as vehicle speed, road condition, weather, etc.), and where colliding with such a hazard or veering off the road would constitute more danger than colliding with the crash cushion or guard rail (Statens vegvesen, 2013). Crash cushions are energy-absorbing structures put up in front of tunnel portals, in front of bridge pillars or in front of fixed obstacles where the road divides into exit ramps. Guard rails are more or less yielding structures intended to prevent a vehicle from veering away from the lane it is intended to follow. The particular designs of this measure which are investigated are guard rails along the roadside, median guard rails on divided highways, and crash cushions.

3.1.3 - Effect on accidents

In general, the primary objective of this safety measure is consequence reduction in case an accident happens, rather than preventing the accident from occurring in the first place. It is however possible that the driver's objective of avoiding the guard rail or crash cushion may indeed reduce the actual number of accidents. As indicated in the introduction of the measure, installing guard rails along the road side may also improve optical guidance, which in turn may improve the driver's vigilance and attentiveness. Concerns about a bloated sense of security as a result of the measure's installation, which may lead to careless driving in dangerous terrain, are raised. The fact that there is less space to perform emergency manoeuvres on divided roads where guard rails are installed between the lanes, is also mentioned as a possible source for increased accident frequency. It is stressed that the net effect of this measure should incorporate both changes in accident probability as well as severity of accident consequences.

Guard rails along the roadside

For this particular safety measure, there is an abundance of available studies for the effects of the measure in its various designs. Guard rails along the roadside are found to strongly reduce the number of off-the-road accidents which result in injury and death. The studies indicate that modifying existing guard rails to be more pliant has damage-reducing potential, although not as much as the installation of guard rails along previously unprotected roadsides. It is mentioned that the guard rails do not have equal effects on every obstacle type. In particular, the measure's severity reduction effect in accidents involving collisions with trees and rock faces, as well as driving off the road in steep slopes, is found to be much greater than this effect on accidents where a vehicle hits a signpost or a ditch. In Table 3.1.1 below, results found in the available studies regarding the effects on accidents of guard rails along the roadside (Elvik et al., 2009) are summarized:

Table 3.1.1: Effects on accidents of guard rails along the roadside (Elvik et al., 2009)

	Percentage change in number of accidents		
Accident severity	*Accident type affected*	*Best estimate*	*95% confidence interval*
New guardrail along embankment			
Fatal accident	Driving off the road	-44	(-54, -32)
Injury accident	Driving off the road	-47	(-52, -41)
Unspecified accident	Driving off the road	-7	(-35, +35)
Changing to softer guardrails			
Fatal accident	Driving off the road	-41	(-66, +2)
Injury accident	Driving off the road	-32	(-42, -20)

Median guard rails on divided highways

Similarly to guard rails along the roadside, significant reductions in accidents which result in injury or death are found with the installation of median guard rails on divided highways. Guard rails made from more yielding materials such as wire or steel are identified as stronger contributors to the reduction effect. Property-damage-only accidents (under "unspecified accident") are however boosted by 24%. The full summary of the data collected about this guard rail type is listed below, in Table 3.1.2 (Elvik et al., 2009):

Table 3.1.2: Effects on accidents of median guard rails on divided highways (Elvik et al., 2009)

	Percentage change in number of accidents		
Accident severity	*Accident type affected*	*Best estimate*	*95% confidence interval*
Median guard rail on multi-lane divided highways			
Fatal accident	All	-43	(-53, -31)
Injury accident	All	-30	(-36, -23)
Unspecified accident	All	+24	(+21, +27)
Type of guard rail in median			
Injury accident	Concrete	+15	(-18, +61)
Injury accident	Steel	-35	(-43, -26)
Injury accident	Wire	-29	(-40, -15)

Median guard rails on undivided highways

A Swedish study published on the effects of median guard rails installed on undivided highways in order to prevent devastating head-on collision events, is presented. The guard rails assessed are made from wire. It is discovered in the study that while total number of accidents is greater than expected, the severity of the accidents is decreased. The results of the study are found in Table 3.1.3 below (Carlsson, 2001; Elvik et al., 2009):

Table 3.1.3: Guard rails to prevent head-on collisions on undivided highways in Sweden (Carlsson, 2001; Elvik et al., 2009)

Number of accidents or injured persons	*Expected (no guard rail)*	*Actual (with guard rail)*
All accidents (including property-damage only)	106	142
Slightly injured persons	47.3	39
Seriously injured persons	15	7
Fatally injured persons	5.2	0

3.1.4 - Effect on mobility

There exists little documentation on this safety measure's effects on vehicular mobility. According to the textbook, the few studies which are available are old and possibly not too relevant for the holistic view on the safety measure. It is stated that most of the studies only refer to guard rails erected on medians of divided highways. The section then lists some study findings, which are listed below (Elvik et al., 2009):

- No significant change in speed was found after the installation of concrete guard rails in the median of the Long Island Parkway in New York (Billion, 1956).
- It was found that installation of similar guardrails on straight road sections lead to an increase in speed on such roads, while a decrease in speed was found for curved roads (Billion, Taragin, & Cross, 1962).
- A study by (Sacks, 1965) found an increase of speed of 3-5 km/h after the installation of median guard rails.
- An increase in mean speed of about 2 km/h was found to be attributable to the installation of guard rails on undivided highways in Sweden (Carlsson, 2001).

3.1.5 - Effect on the environment

There are no studies available which assess the effect of guard rails on the environment. It is mentioned that guard rails "probably" have no effect on noise or air pollution, and that it is possible that guard rails may increase barrier effects of a road for pedestrians, cyclists, emergency vehicles and game.

3.1.6 - Costs

Table 3.1.4 below summarizes results from a cost-benefit analysis conducted by (Elvik, 2001b), and includes considerations on crash cushions collected from studies by Griffin (1984) and Viner and Tamanini (1973):

Table 3.1.4: Costs of guard rails. Norwegian data (Elvik, 2001b; Elvik et al., 2009)

	Unit cost (1 km guard rail or 1 crash cushion)	
Type of guard rail	*Investment (NOK)*	*Annual maintenance (NOK)*
Steel, 4 m between poles, no blocking	250,000	7,500 - 15,000
Steel, 4 m between poles, blocking	280,000	8,000 - 16,000
Steel, 2 m between poles, no blocking	350,000	10,000 - 20,000
Steel, 2 m between poles, blocking	400,000	12,000 - 24,000
Concrete	750,000	25,000 - 50,000
Wire	300,000	20,000 - 40,000
Crash cushion	150,000	5,000 - 10,000

3.1.7 - Cost-benefit analysis

The study used to calculate the estimates listed in Table 3.1.4 above shows that guard rails installed along embankments are projected to provide benefits greater than associated costs under the condition that the roads have an AADT of about 3000 or more. Roads that have lighter traffic than this have an expected number of accidents which is too small to offset installation costs. It is also found that guard rails installed on undivided highways in order to prevent head-on collisions are cost-effective if the road carries an AADT of at least 5000 (Elvik, 2001b). Benefit-cost ratio is found to be 2, for both new installations of guard rails and maintaining existing constructs.

3.2 - Safety measure: grade-separated junctions

3.2.1 - Problem and objective

A grade-separated junction (or interchange) is a junction which is designed such that traffic lanes are separated by elevation, thereby reducing conflicts between traffic streams, queues caused by heavy traffic, and the need for complex manoeuvring when changing lanes. The main objective of this safety measure is to streamline the flow of traffic in order to reduce the chances of accidents occurring.

3.2.2 - Description of measure

As already stated, the general design of the measure involves segregation of traffic lanes by grade-separation. If the junction is fully grade-separated, there is no need for movements which require the crossing of other traffic streams. Disruptive movement is reduced to lane changes in the same direction, in order to assume a new junction level. Although many different designs of grade-separated junctions exist (such as diamond interchanges, trumpet interchanges and partial/full cloverleaf interchanges), the basic principles are the same.

3.2.3 - Effect on accidents

The effects of grade-separated junctions on accidents are largely estimated in relation to accident rates on level (at-grade) junctions. Different effects of varying grade-separation designs with varying design elements are also estimated and compared.

Grade-separated junctions instead of at-grade junctions

A comparison of accident rates for grade-separated- and at-grade junctions reveals the results summarized in Table 3.2.1 below (Elvik et al., 2009). The greatest implied accident reducing effect of replacing an at-grade junction with a grade-separated junction, is found in X-junctions. As displayed, the injury accident reduction effect is larger than that of property-only accidents. It is specified that the qualifier "accidents in the area of the junctions" includes accidents on ramps for grade-separated junctions, but not accidents on what could be considered comparable stretches of road leading up to and just immediately following at-grade junctions. This clarification is proceeded by an assurance that if such accidents were to be counted, even greater accident reduction effects would be recorded. It is argued that the ramps in grade-separated junctions constitute new road elements once the grade-separated junction is built, the effect of which is essential to include in the assessment of the accident reducing effect of grade-separated junctions. One German study in particular investigates the effect of partly grade-separated junctions, which are found to be "less safe than grade-separated junctions, but safer than at-grade X-junctions" (Elvik et al., 2009). It is also found that at-grade X-junctions equipped with speed cameras are safer than partly grade-separated junctions where no such cameras are installed, and there is no significant difference in safety between a partly grade-separated junction and a signalized junction.

Table 3.2.1: Effects of grade-separated junctions on accidents in the area of the junctions (Elvik et al., 2009)

	Percentage change in number of accidents		
Accident severity	*Accident type affected*	*Best estimate*	*95% confidence interval*
T-junction: grade-separated instead of at-grade			
Unspecified accident	All accidents	-16	(-33, +4)
Injury accident	All accidents	-24	(-57, +33)
X-junction: grade-separated instead of at-grade			
Unspecified accident	All accidents	-42	(-52, -30)
Injury accident	All accidents	-57	(-62, -51)
Property damage only accident	All accidents	-36	(-50, -19)
Signalized junction: grade-separated instead of at-grade			
Unspecified accident	All accidents	-27	(-36, -18)
Injury accident	All accidents	-28	(-40, -15)
Grade-separated junctions instead of partly at-grade junctions			
Unspecified accident	All accidents	-15	(-24, -5)
Partly grade-separated junction instead of at-grade X-junction			
Unspecified accident	All accidents	-26	(-38, -13)
Partly grade-separated junction instead of at-grade X-junction with speed camera			
Unspecified accident	All accidents	+115	(+52, +205)
Partly grade-separated junctions instead of signalized junctions			
Unspecified accident	All accidents	-22	(-41, +3)

Effects of the design of grade-separated junctions

This section compares the effects of diamond interchanges with other designs of grade-separated junctions. The effects on accidents of various grade-separated junction design elements are also assessed, where information is available. Such elements include the layout of the junction, lanes used for merging and acceleration/deceleration, ramp type, curve-radius of the ramps, and lane number. All study results refer to comparison of accident rates between intersection types or variants of design elements of interchanges. It is clarified that none of the available studies evaluate the effects of converting an interchange into a different type of interchange. Results comparing diamond interchanges to other interchange types are listed below in Table 3.2.2 (Elvik et al., 2009). In short, diamond interchanges are found to have comparably lower accident rates than most other interchange types. The greatest favourable comparison is found with trumpet interchanges and junctions with direct access ramps. Most other comparisons yield minor or insignificant differences. It is discussed that the relative superior safety rating found in diamond interchanges, is due to factors such as a simple layout which minimizes driver confusion and erroneous driving, and use of straight ramps, which have lower accident rates than curved ramps (see Table 3.2.3).

Table 3.2.2: Effects on accidents in the area of intersections of diamond interchanges compared to other types of interchanges (Elvik et al., 2009)

	Percentage change in number of accidents		
Accident severity	*Accident type affected*	*Best estimate*	*95% confidence interval*
Diamond instead of trumpet			
Unspecified	All accidents	-38	(-59, -7)
Diamond instead of junction with direct access ramps			
Unspecified	All accidents	-25	(-59, +40)
Diamond instead of clover-leaf			
Unspecified	All accidents	-2	(-19, +18)
Diamond instead of loop			
Unspecified	All accidents	-9	(-25, +10)
Diamond instead of other			
Unspecified	All accidents	-7	(-17, +4)
Diamond instead of other			
Unspecified	Truck accidents, not on ramp	-11	(-23, +3)
Diamond instead of other, excluding loop			
Unspecified	Truck accidents on ramps	+43	(+33, +54)
Diamond instead of loop			
Unspecified	Truck accidents on ramps	-10	(-20, +2)
Tight Urban Diamond Interchange (TUDI) instead of Single-Point Urban Interchange (SPUI)			
Unspecified	All accidents	+2	(-11, +17)

In addition to this design investigation, the effects of various design elements generally connected to junctions is collected in Table 3.2.3 below. Primary findings of particularly noteworthy studies are then listed and commented on (Elvik et al., 2009).

Table 3.2.3: Effects on accidents in the area of intersections of design elements of grade-separated junctions (Elvik et al., 2009)

	Percentage change in number of accidents		
Accident severity	Accident types affected	Best estimate	95% confidence interval
Ramp types			
Unspecified	Straight ramp instead of clover-leaf	-45	(-60, -25)
Unspecified	Clover-leaf instead of long ramp	-23	(-39, -3)

Unspecified	Long ramp instead of short ramp	-38	(-49, -24)
Unspecified	Short ramp instead of loop	-30	(-45, -10)
Straightening of curves on ramps (larger curve radius)			
Unspecified	Accidents on ramps	-13	(-36, +17)
Crossroad above instead of below main road			
Unspecified	All accidents	-4	(-17, +10)
Extension of acceleration lane by 30 m			
Unspecified	Accidents in acceleration lane	-11	(-17, -5)
Extension of deceleration lane by 30 m			
Unspecified	Accidents in deceleration lane	-7	(-13, 0)
Extension of acceleration and deceleration lanes by 30 m			
Unspecified	Accidents in acceleration and deceleration lanes	-5	(-11, +2)
Merging lanes requiring less than 2 lane changes instead of merging lanes requiring 2 lane changes for driving on or off the ramp			
Unspecified	Accidents in merging lane	-32	(-36, -27)
4-lane road instead of 2-lane road			
Unspecified	All accidents	+30	(+5, +61)
Off-ramp instead of on-ramp			
Unspecified	Accidents on ramps	+73	(+70, +75)

The following points are findings of particular interest found in certain studies, showcased below the result tables (Elvik et al., 2009):

- A variety of results were discovered in a study on truck accidents in different types of grade-separated junctions, by Janson, Awad, Robles, Kononov, and Pinkerton (1998). It was found that when accidents on ramps were excluded from the calculation, the diamond interchange appeared to be the safest interchange type for trucks. The accident rates of trucks on ramps in diamond interchanges were found to be lower than on loop ramps, but higher than on other ramp types. Accident rates of trucks on grade-separated junctions were found to be lower for high traffic volumes than for low traffic volumes.
- No significant difference in accident rate was found between TUDI and SPUI (J. C. Lee, Larwin Jr, Kidd, & Bonneson, 2002).
- Studies on accident rates on different ramp types by McCartt, Northrup, and Retting (2004) and Janson et al. (1998) arrived at evidence which corroborates findings from comparisons between different layouts of grade-separated junctions. The studies suggest that accident rates on ramps increase in the following order: straight ramp,

clover ramp, long ramp, short ramp, loop. The lowest accident rates were found in diamond interchanges, which are constructed solely with straight ramps.

- Accident rates on grade-separated junctions where side roads crosses over, rather than under, the main road appear to be lower; it is hypothesized improved sight conditions for merging traffic may be the cause. For acceleration and deceleration lanes up to 200 m of length, a relationship between accident rate and road length was found. This relationship was not present for longer acceleration and deceleration lanes. The most common accident types associated with ramps were found to be road departure and rollover accidents (Janson et al., 1998; McCartt et al., 2004).
- A study investigating merging lanes by Golob, Recker, and Alvarez (2004) reported that accident rates increase with the required number of lane changes for accessing or exiting ramps.
- Accident rates on grade-separated junctions are higher for 4-lane roads than for 2-lane roads, contrary to on sections, where 2-lane roads have higher accident rates.
- A study conducted on the difference between on- and off-ramps by McCartt et al. (2004) concluded that generally, there are higher accident rates found on off-ramps than on on-ramps. Road departure accidents have been found to be three times as frequent on off-ramps compared to on on-ramps. Rear-end collision accidents appear to be about equally frequent on off- and on-ramps. Side-impacts happen twice as frequently on on-ramps compared to on off-ramps.
- Ramp metering, a measure which increases the capacity of grade-separated junctions by preventing large groups of vehicles to enter at once, was found in studies by Cambridge Systematics (2001) and C. Lee, Hellinga, and Ozbay (2006) to reduce stop-and-go traffic and fuel consumption, as well as having collision-reducing properties.

3.2.4 - Effect on mobility

A grade-separated junction is constructed in places where high-velocity travel is desired, and heavy traffic flows prevent vehicles from satisfactorily traversing interchanges. More directly speaking, the objective of a grade-separated junction is to act as an interchange where more vehicular mobility is maintained. It is therefore reasonable to assume that installation of grade-separated junctions will in most situations contribute positively to mobility. Model calculations based on general relationships between traffic levels, capacities and waiting times at intersections by Elvik (1993) discovered that average time saved per car at interchanges is between 5 and 15 seconds. Other studies have found that this number relies on traffic volumes. Acceleration lanes are also found to have positive effects on driving speeds.

3.2.5 - Effect on environment

No particular environmental effects related to grade-separated junctions are mentioned in any available studies. It is postulated that the size requirement for installing such a structure may be experienced as intrusive on the landscape, and obstructing to the view of near-by inhabitants. Small pollutant-reducing effects may be achieved by a reduction of needed braking and re-accelerating.

3.2.6 - Costs

The average cost of constructing a grade-separated junction is estimated based on figures for a small number of interchanges built in Norway, to be at around NOK 40 million (Elvik, 1996). It is further stressed that the number arrived at is very uncertain, and that costs depend on many different factors including interchange type and space required to build.

3.2.7 - Cost-benefit analysis

A numerical example is worked out in this sub-section. The costs and benefits of converting an at-grade X-junction into a grade-separated junction. The hypothetical junction is assumed to have an AADT of 20,000 vehicles, and an accident rate of 0.25 injury accidents per million vehicles entering. It is assumed that the conversion of the X-junction into a grade-separated junction manages to reduce the number of injury accidents by 50%, and that each vehicle that passes through the intersection saves 10 seconds. Under this set of assumptions, the calculated benefits in the form of saved accident costs become NOK 41.5 million, while the benefits in terms of reduced travel time costs amount to NOK 46.6 million. The total expected benefit of the conversion becomes NOK 88.2 million, which is more than double that of the expected cost of constructing the structure. The overall benefit-cost ratio is evaluated at 2.2.

3.3 - Safety measure: roundabouts

3.3.1 - Problem and objectives

At junctions which are subject to heavy traffic and queue build-up, a particular problem of driver impatience appears. In order to escape the stand-still, drivers feel prompted to "take a chance" and enter the junction in traffic gaps with small safety margins. Such behaviour, coupled with the already complex traffic scenario that is created in junctions by frequent crossing and turning manoeuvres from all directions, contribute to a rather dangerous traffic environment. Roughly 40% of all police-reported injury accidents take place at intersections (Elvik et al., 2009). Roundabouts are conversions of junctions into a safer driving setting. The objective of the safety measure is to improve traffic safety by slowing down and regulating traffic flows. Since all vehicles that want to enter a roundabout must give way to all vehicles currently in the roundabout, a much higher degree of attentiveness to traffic is demanded of the driver. Roundabouts direct all traffic so that it flows in only one direction, simplifying the process of discovering gaps to enter them. Vehicle speed is slowed considerably, as the roundabout forces drivers around a traffic island rather than letting them speed through in a straight line. This ensures safety and increases time available to react, should a dangerous situation appear.

3.3.2 - Description of the measure

A roundabout is a road intersection with circulatory traffic streams. In countries where drivers drive on the right side of the road, traffic in roundabouts is regulated and directed anti-clockwise around a sturdy traffic island placed in its centre. Most roundabouts operate with offside priority, meaning that vehicles already in the roundabout have priority over vehicles that have yet to enter. All results presented here refer to roundabouts with offside priority.

3.3.3 - Effect on accidents

Table 3.3.1 at the end of this sub-section summarizes study findings on the general accident-reducing effects of converting a junction into a roundabout. Overall, the greatest effect is found for accidents which result in fatality. An increase in property damage accidents is noted, but deemed to be insignificant considering the otherwise rather positive effects found by the safety measure. With a great deal of available knowledge in the form of studies for this particular safety measure, many findings are listed and discussed beneath the table of results. The following points are brought up and given particular attention (Elvik et al., 2009):

- The studies revealed that converting previous yield junctions and X-junction to a roundabout causes a particularly stronger reduction in accidents, when compared to conversion of other junction types. Conversions in rural areas were found to have greater accident-reducing effects than in urban areas. It is possible that this is related to findings from studies by De Brabander, Nuyts, and Vereeck (2005), effects of roundabouts are greater when the speed limit is higher.

- There has not been found any significant differences in roundabout effects in different countries (Elvik, 2003). Results from assessment on roundabout effects are found to not be particularly affected by publication bias. A meta-regression analysis conducted shows that all factors represented in Table 3.3.1 below are significant predictors for the effectiveness of roundabouts, although since the results show a large degree of heterogeneity, it is likely that the effectiveness of roundabouts is affected by other factors as well as the ones assessed here (Elvik et al., 2009).
- Studies by Cedersund (1983a) and Maycock and Hall (1984) failed to discover a relationship between size of traffic island and accident rates. These studies went out of their way to control for other factors which may have influenced the results.
- Studies by Tran (1995) and Brüde and Larsson (1999) found higher injury accident rates in larger roundabouts than in small ones. These results are uncertain, however, as no effort is made to control for other factors that may have affected the accident rate.
- The relationship between speed limits and accident rates in roundabouts was investigated in a study by E. Jørgensen and Jørgensen (2002). It was found that accident rates are greater in roundabouts which require larger speed reductions on roads where the speed limit is 80 km/h. Such a relationship was not proven for roads with lower speed limits.
- On the effects of roundabouts on accident rates for various groups of road users, some studies (N. O. Jørgensen, 1991; Lalani, 1975; Schoon & Van Minnen, 1993; Van Minnen, 1990) discovered that pedestrian accident rates are reduced to a similar extent as for vehicles, while the effect is slightly smaller for cyclists. The results from the studies are however deemed uncertain, as there are great discrepancies and conflict among them (Elvik et al., 2009).

Table 3.3.1: Effects on accidents of converting intersections to roundabouts (Elvik et al., 2009)

	Percentage change in number of accidents		
	Accident severity	*Best estimate*	*95% confidence interval*
All roundabouts	All severities	-36	(-43, -29)
All roundabouts	Fatal accidents	-66	(-85, -24)
All roundabouts	Injury accidents	-46	(-51, -40)
All roundabouts	Property damage only accidents	+10	(-10, +35)
Previous yield junctions	All severities	-40	(-47, -31)
Previous signalized junctions	All severities	-14	(-27, +1)
X-junctions	All severities	-34	(-42, -25)
T-junctions	All severities	-8	(-28, +18)
Roundabouts in rural areas	All severities	-69	(-79, -54)
Roundabouts in urban areas	All severities	-25	(-34, -15)

3.3.4 - Effect on mobility

Due to the removal of both crossing and turning manoeuvres, which tend to lead to waiting time and other traffic delays, roundabouts have higher traffic capacity than both regulated give-way intersections and signalized junctions. The following results are gathered on the effects of roundabouts on traffic mobility (Elvik et al., 2009):

- Even though the construction of roundabouts generally leads to slower speeds among vehicles (Senneset, 1983), total passing time through roundabouts tend to be shorter than through other intersection types.
- It is difficult to gather precise figures on time saved by driving in a roundabout rather than an intersection. Results from a German study by Brilon and Stuwe (1991) showed that average waiting time per vehicle is 15 seconds shorter at roundabouts than at intersections with traffic lights with an hourly traffic flow between 500 and 2,000 vehicles.
- A Swedish study, in which the conversion of 20 intersections with give-way regulations into roundabouts was investigated (Várhelyi, 1993), found that vehicles entering from main roads lost an average of 2.3 seconds per intersection (per vehicle) when these had been converted into roundabouts. Entering from minor roads, vehicles experienced an average time gain of 4.4 seconds per intersection (per vehicle). The study results were gathered from intersections with an average of 9,700 vehicles entering from main roads during a 24 hour period, this number being 3,130 vehicles for side roads during the same period.
- The same study (Várhelyi, 1993) found that the conversion of a signalized junction with 23,500 incoming vehicles per day into a roundabout, resulted in an average time gain of 10.1 seconds per vehicle.

3.3.5 - Effect on environment

A few studies are found on the effects of junction conversion into roundabouts on the environment. Relevant results are listed below (Elvik et al., 2009):

- Bendtsen (1992) found that emissions of hydrocarbons (HC), nitrogen oxide (NO_X) and carbon monoxide (CO) were around 5-10% lower in roundabouts than in signalized junctions. The emissions were calculated in grams per kilometre driven per car.
- Várhelyi (1993) found decreased emissions of both carbon monoxide (29%) and of nitrogen oxide (21%) after the conversion of signalized junctions into a roundabouts. For previously give-way regulated intersections, less favourable results were obtained. After such conversions, increases in emissions of carbon monoxide (6%) well as nitrogen oxide (4%), were discovered.

3.3.6 - Costs

Building costs of roundabouts may vary from several hundred thousand kroner to NOK 5-10 million. According to a collection of information assembled by Elvik and Rydningen (2002), the mean cost of converting a 3-leg junction into a roundabout in Norway is roughly NOK 4.8 million. For 4-leg junctions, this figure is found to be NOK 3.5 million.

3.3.7 - Cost-benefit analysis

The main source of information on which the cost-benefit analysis on construction of roundabouts in Norway, is the data collection by Elvik and Rydningen (2002). For 3-leg junctions, mean AADT is found to be 9,094 and mean accident rate is 0.23 injury accidents per million vehicles entering. The latter value is of particular interest, as it is substantially higher than normal accident rates for 3-legged junctions in Norway (Elvik et al., 2009). With a discount rate of 5% and project lifetime of 25 years, the benefits of converting a typical 3-leg junction into a roundabout are estimated to be NOK 9.15 million. Similar calculations estimate the costs of the conversion to be NOK 5.15 million. For 4-leg junctions, mean AADT is found to be 10,432 and mean accident rate is 0.15 injury accidents per million entering vehicles. In this case, the latter value coincides to normal accident rates for 4-legged junctions (Elvik et al., 2009). Estimated benefits of converting a 4-leg junction into a roundabout are about NOK 9.2 million, while costs are estimated to be NOK 4.16 million. As benefits are greater for both cases, it appears that this safety measure is cost-effective, at least at the traffic volumes observed in the data collection. The book lists benefit-cost ratios for roundabouts at crossroads and at T-junctions, at 2.2 and 1.8 respectively.

3.4 - Assessing the background knowledge

There is a need to be critical of the context in which a project is being considered. A proper assessment of uncertainties related to available information and assumptions about the various aspects of the project should be conducted. In this section of the thesis, the three safety measures from *The Handbook of Road Safety Measures* (Elvik et al., 2009) are assessed with respect to and ranked based on the strength of knowledge used in their cost-benefit analyses. This comparison of information bases is tailored towards challenges the authors of the book may have encountered when performing the literature study for the book, and is based primarily on the authors' own comments on the results displayed in the book, meaning that the strength of knowledge assessments of the measures which are presented in this thesis are made in relation to each other. If a verdict of weak background knowledge is given, as stated in the paragraph on limitations in the beginning of the thesis, this means that the knowledge is seen as comparatively weaker than the other investigated information bases. This method of knowledge assessment is deemed sufficient for the purposes of the thesis.

The section on assessment of background knowledge also includes a visual representation of the results. As exemplified in work by E. B. Abrahamsen, Selvik, and Berg (2016), where risk/cost-effectiveness and prediction quality matrices are used to display results, and by E. B. Abrahamsen, Aven, and Røed (2009), where a new visualizing tool which includes three different decision dimensions is presented, the translation of information between analyst and decision-maker is of vital importance to ensure that an informed decision may be made. Since the background knowledge assessment results in a verdict of strong, medium or weak knowledge, there is little need to over-complicate matters, and considering the topic of the thesis, an apt design for the visual representation is chosen, as displayed in Figure 2 below:

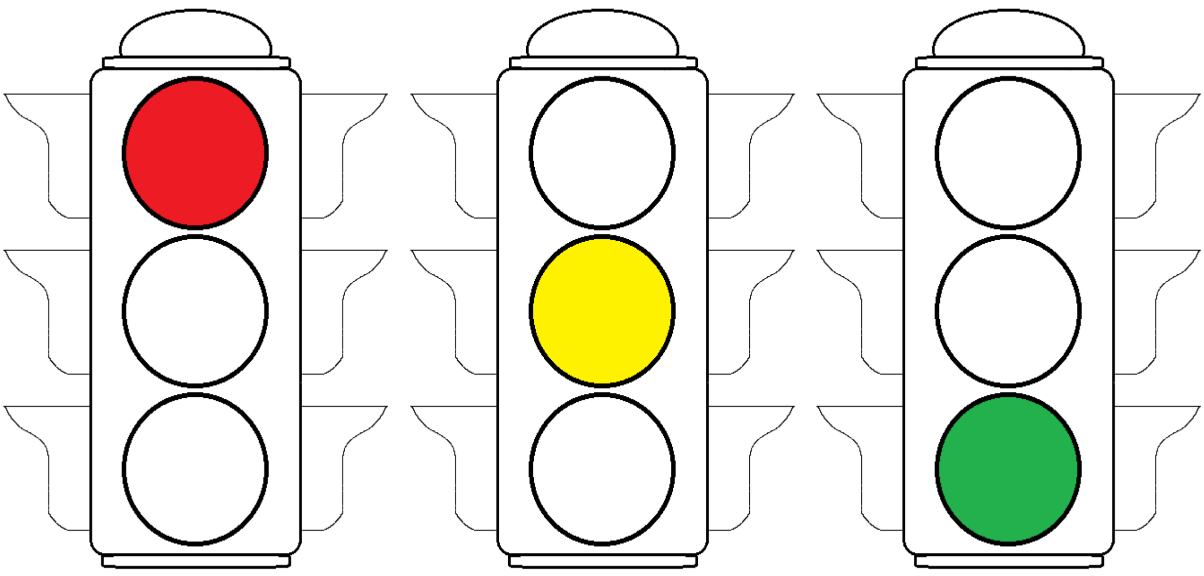


Figure 2: Visual representation of strength of knowledge; weak, medium and strong

The general idea is for a new section to be added to *The Handbook of Road Safety Measures* (Elvik et al., 2009) in which the studies used to gather results for the cost-benefit analyses are assessed. The authors of the book can talk about important assumptions made in collecting and interpreting the studies, as well as discuss their thought processes and methodology for why certain studies are included or excluded. The section should help the authors to convey to the reader why the results of the safety measure cost-benefit analyses look the way they do. The section does not have to be exhaustive; a small paragraph containing considerations on how the authors view their own use of results found in the studies, whether they believe the studies provide strong, medium or weak knowledge, how confident the authors are in presenting their results with the studies as a basis, and why this is the case. Finally, the section can be supplemented with one of the traffic light figures presented in Figure 2, to visually illustrate their strength of knowledge.

In order to demonstrate this idea, the thesis presents three sub-sections describing the extent of background knowledge assessment indirectly conducted by the authors of *The Handbook of Road Safety Measures* (Elvik et al., 2009), which mostly done in the form of comments on certain studies which present particularly interesting findings. After this, a sub-section which discusses these comments and subsequently assesses the perceived strength of knowledge for each safety measure is presented, followed by a comparison of both benefit-cost ratios and strength of knowledge for each measure.

3.4.1 - Guard rails and crash cushions: knowledge assessment

Accident rates

The effects on accident rates by guard rails on the sides of the road, guard rails installed as medians on divided and undivided highways, and crash cushions listed in *The Handbook of Road Safety Measures* (Elvik et al., 2009) are gathered from the following sources:

(Glennon & Tamburri, 1967)
(Tamburri, Hammer Jr, Glennon, & Lew, 1969)
(Williston, 1969)
(Good & Jobert, 1971)
(Woods, Bohuslav, & Keese, 1976)
(Pettersson, 1977)
(Ricker, Banks, Brenner, Brown, & Hall, 1977)
(Perchonoc, Ranney, Baum, Morris, & Epich, 1978)
(Schandersson, 1979)
(J. W. Hall, 1982)
(Boyle & Wright, 1984)
(Bryden & Fortuniewicz, 1986)
(Domhan, 1985)
(Schultz, 1986)
(Beaton, Field, & Moskowitz, 1962)
(Billion & Parsons, 1962)
(Billion et al., 1962)
(Sacks, 1965)
(R. T. Johnson, 1966)
(Moore & Jehu, 1968)
(Galati, 1970)
(Tye, 1975)
(Andersen, 1977)
(H. D. Johnson, 1980)
(Statens vägverk, 1980)
(Martin et al., 1998)
(Sposito & Johnston, 1998)
(Hancock & Ray, 2000)

(Ray, Troxel, & Carney III, 1991)
(Hunter, Stewart, & Council, 1993)
(Gattis, Alguire, & Narla, 1996)
(B. F. Corben, Deery, Mullan, & Dyte, 1996)
(Short & Robertson, 1998)
(Ljungblad, 2000)
(Billion, 1956)
(Moskowitz & Schaefer, 1960)
(Nilsson & Ljungblad, 1999)
(Hunter et al., 2001)
(Viner & Tamanini, 1973)
(Griffin, 1984)
(Kurucz, 1984)
(Schoon, 1990)
(Proctor, 1994)

For guard rails along the roadside, the results of the studies are more or less unanimous in that they show great decrease in number of fatal off-road accidents. It is however mentioned that this effect is uncertain and probably smaller for the total number of all types of accidents. Changing existing guard rails into more pliant material is commented on as being less effective than installing guard rails in new places. It is also mentioned that the guard rails are not equally effective on every obstacle type.

For median guard rails on divided highways, great reductions in fatal and injury accidents are found, with greater effects found for yielding materials. In addition, the book finds increases in property-damage accidents associated with the measure. For median guard rails on undivided highways, the book cites two studies on wire guard rails installed between lanes on undivided highways. The evaluation of these studies reveals that although number of accidents increased as a result of the installation, the overall severity of the accidents decreased. These results are mentioned without additional comments.

For crash cushions, large reductions in fatal, injury and property-damage accidents are found. However, the book comments that the results from the studies display significant heterogeneity, which could indicate that the results are affected by regression to the mean.

Mobility and environment

The sections detailing effects of guard rail installation on vehicle mobility and surrounding environment cite a lack of much available information as a source of uncertainty. It is commented that most of the studies on mobility only refer to guard rails installed as medians on divided highways, and may be outdated due to their age. The book states that studies on the effects of guard rails and crash cushions on the environment could not be found at all.

3.4.2 - Grade-separated junctions: knowledge assessment

Accident rates

The effects on accident rates measured by comparison of accident rates on at-grade and grade-separated junctions, as well as different grade-separation designs, listed in *The Handbook of Road Safety Measures* (Elvik et al., 2009) are gathered from the following sources:

(Hvoslef, 1974)
(Statens vägverk, 1983)
(Tie- ja vesirakennushallitus, 1983)
(Johansen, 1985)
(Pajunen, 1999)
(Tielaitos, 2000)
(Meewes, 2002)
(Lundy, 1967)
(Cirillo, 1968, 1970)
(Yates, 1970)
(Wold, 1995)
(Bauer & Harwood, 1998)
(Janson et al., 1998)
(Khorashadi, 1998)
(Bared, Giering, & Warren, 1999)
(J. C. Lee et al., 2002)
(Golob et al., 2004)
(McCartt et al., 2004)

For grade-separated junctions instead of at-grade junctions, accident rates between at-grade and grade-separated junctions are compared. The book identifies lower accident rates for grade-separated junctions, with the greatest difference found between these and X-junctions. It is commented that accidents in close proximity to the entrances and exits of at-grade junctions are excluded from the analysis, while accidents on ramps in grade-separated junctions are counted, indicating that larger differences in accident rates could possibly be found. Various results on other aspects of the safety measure, such as partial grade-separation, the presence of speed cameras, and comparisons to signalized junctions, are listed without comments.

For effects of different designs of grade-separated junctions, most results are presented relatively straight-forwardly without additional discussion from the authors. It is commented that results pertaining to accident rates connected to ramp types coincide with results from studies investigating accident rates in different layouts of grade-separated junctions, as well as with a study which concluded that lower accident rates are found on straight ramps.

Mobility and environment

On the effects of grade-separated junctions on vehicle mobility, results gathered in the book are taken from studies using model calculations based on "general relationships between traffic levels, capacity and waiting times at intersections" (Elvik et al., 2009). Effect on mobility is therefore comprised of estimated values, which are not taken from real-world measurements or tests. As for with guard rails and crash cushions, the book is unable to find any studies on the effects of grade-separated junctions on surrounding environment.

3.4.3 - Roundabouts: knowledge assessment

Accident rates

The effects on accident rates by installing roundabouts in place of various intersection types listed in *The Handbook of Road Safety Measures* (Elvik et al., 2009) are gathered from the following sources:

(Lalani, 1975)
(Green, 1977)
(Lahrmann, 1981)
(Cedersund, 1983a, 1983b)
(Senneset, 1983)
(Brüde & Larsson, 1985)
(Johannessen, 1985)
(R. D. Hall & McDonald, 1988)
(Bruce F Corben, Ambrose, & Foong, 1990)
(Giæver, 1990)
(Tudge, 1990)
(Van Minnen, 1990)
(N. O. Jørgensen, 1991)
(Brüde & Larsson, 1992)
(Dagersten, 1992)
(Holzwarth, 1992)
(Hydén, Odelid, & Várhelyi, 1995)
(Værø, 1992a, 1992b, 1992c, 1992d)
(Brilon, Stuwe, & Drews, 1993)
(Huber & Bühlmann, 1995)
(E. Jørgensen & Jørgensen, 1994)
(Schoon & Van Minnen, 1993)
(Seim, 1994)
(Voß, 1994)
(BTCE, 1995)
(Oslo veivesen, 1995)
(Flannery & Datta, 1996)
(Giæver, 1997)
(Flannery, Elefteriadou, Koza, & McFadden, 1998)
(Mountain, Maher, & Fawaz, 1998)
(Persaud, Retting, Garder, & Lord, 2001)
(Newstead & Corben, 2001)
(De Brabander et al., 2005)
(Traffic Engineering Branch, 2005, 2007)
(Meuleners, Hendrie, Legge, & Cercarelli, 2005)
(Meuleners, Hendrie, Lee, & Legge, 2008)

The assessment of converting intersections to roundabouts is very straight-forwardly done. The section on the measure's effects discusses which of the investigated interchange types exhibited the greatest effect when converted into roundabouts, what type of accident was reduced the most as a result, effect differences in rural and urban areas as well as in different countries, accident reducing effect for various groups of road users, and the influence of speed reduction requirements and traffic island size on the accident reducing effects. The book makes an effort to corroborate several results with studies by other authors, thereby strengthening the confidence in the conclusions made. It is commented that the studies used for the analysis appear to be more or less unaffected by publication bias, as no particular difference was discovered for roundabout in different countries. Studies on the relationship between the size of traffic the central island and accident rates in roundabouts are commented on as being thorough in accounting for various other factors which may have influenced their results. References are also made to a meta-study conducted to summarise and formulate the results in the book, where the conclusion is that while all factors represented in the result table seem to be significant predictors on the effectiveness of roundabouts, the great heterogeneity exhibited in the results indicates that this effectiveness is likely to be affected by factors not considered by the analysis (Elvik et al., 2009). Studies investigating the effect of roundabout size on accident rates are commented on, and their results are labelled "uncertain" due to the absence of consideration on other factors which may have influenced the results.

Mobility and environment

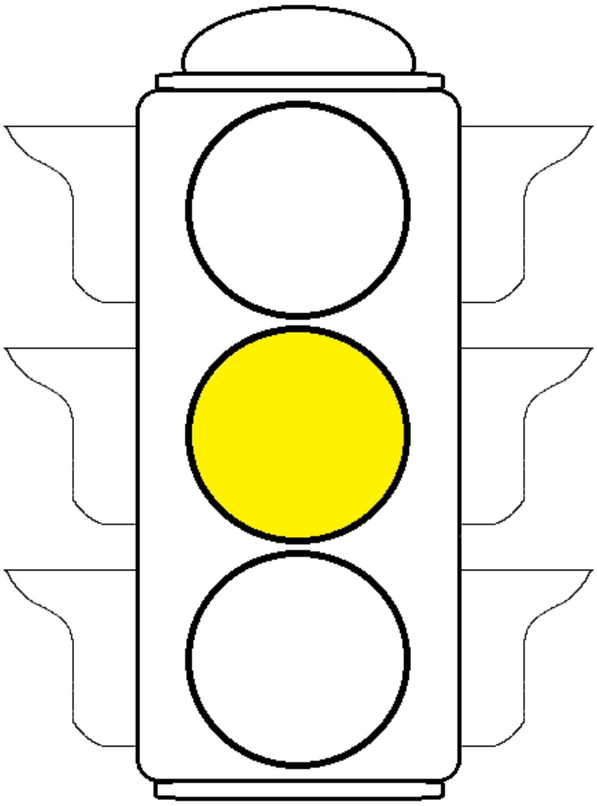
The section on the effects of roundabouts on vehicle mobility concerns itself mostly with time saved while passing through a roundabout as compared to travelling through an intersection. The book comments on the difficulty of providing precise numbers for average time saved, due to the complexity of the traffic situation. The book lists traffic amounts, variation in traffic over 24-hour periods and the distribution of entering vehicles between approaches towards the intersection as influencing factors. After this clarifying statement, some study results are presented with added details about the conditions the effects were measured, such as hourly traffic flow, road type the vehicles arrive from, and average number of entering vehicles. For effects on surrounding environment, the book identifies and summarises two studies on air pollutant concentration in roundabouts and junctions.

3.4.4 - Comparing the safety measures

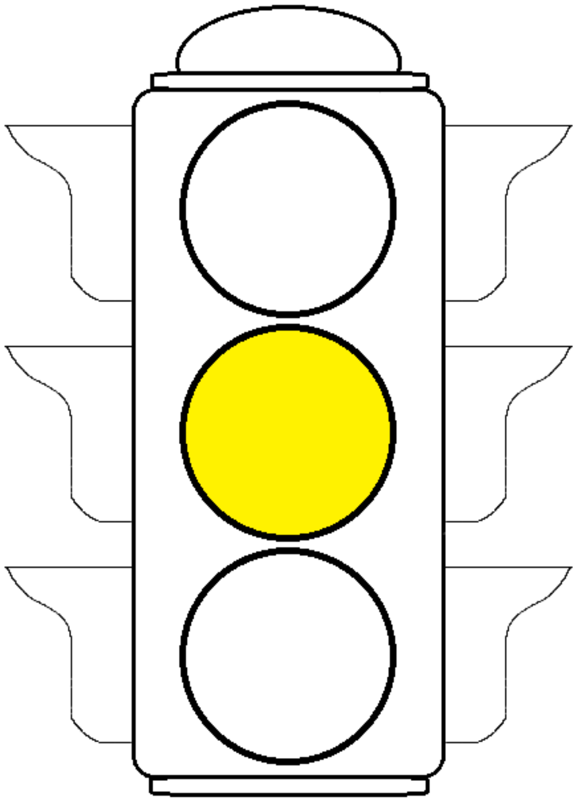
This sub-section of the thesis contains assessments and comparison of strength of knowledge associated with the investigated safety measures.

Guard rails and crash cushions

In *The Handbook of Road Safety Measures* (Elvik et al., 2009), the results from this safety measure assessment are largely presented without comment. It is not clear whether this is because the authors are sufficiently confident about most aspects of the gathered evidence from the studies. Since comments are provided for uncertainty in the safety measure's effect on number of all types of accidents, as well as for overall effect of crash cushions on accident rates, it can appear as if the omission of such comments on other aspects of the result summary suggests this. Although the section cites a long list of sources, the fact that so many of them approach 30-40 years of age (calculated from the publication year of the book) is rather worrying. The fact that studies are old may not always be a problem, but considering how quickly the world of traffic is able to evolve (for example with technological advances), it is possible that many of the sources used to gather information on this safety measure's effects on accidents are more or less outdated.

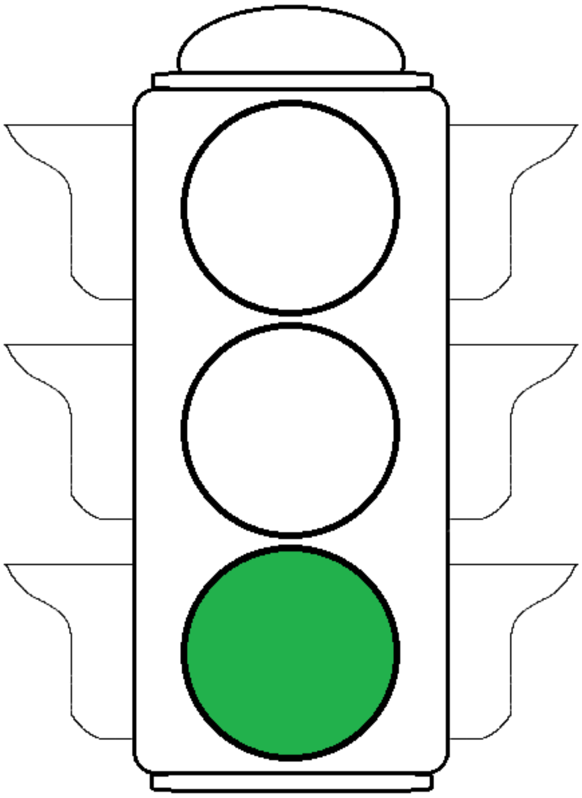


Grade-separated junctions



Studies used in the assessment of grade-separated junctions investigate many different aspects of the constructs. Attention is focused on comparisons of accident rates on grade-separated junctions and various different types of at-grade junctions, and accident reducing effects of different designs of grade-separated junctions. The results presented in the book appear thoroughly researched; studies are collected from various decades of traffic work with no majority favouring a particular period of time. The book does identify corroborative results from several of the studies for this safety measure, as well as an aspect omitted from the analysis which may lead to an underestimated calculated value for the safety measure's effect on accident rates. Results on mobility are cited as being gathered from model calculations, but no additional comment on the validity of such methodology is included. Absence of comments on most of the other results which are elaborated upon may indicate either confidence in the reliability of the studies, or inability to identify supporting evidence.

Roundabouts



The analysis on the effects of roundabouts on accident rates as compared to those of junctions is discussed quite a lot in *The Handbook of Road Safety Measures* (Elvik et al., 2009). The list of sources features several recent studies (calculated from the publication year of the book), and comparatively fewer studies which risks presenting outdated results due to old age. Several studies are commented on as showing corroborative results, and when studies appear to have conducted their analyses differently, the book makes a comment on it. Comparisons of studies from different countries rule out the issue of publication bias. References are made to a meta-regression analysis, which is commented on as indicating that other factors than those assessed in the studies may have influenced the results. The studies on roundabout effect on accident rates for different road users are discussed and commented on as showing highly conflicting evidence and uncertain results. These results are not presented in the result table in the book, presumably for this reason.

Comparative comments

From reading the sections on the various safety measures, it is clear that the assessment of roundabouts contains the most additional discussion on the studies used. Almost all results mentioned in text are supplemented with additional comments on either supporting results from other studies, or factors which may render the results less applicable. The verdict of strong background knowledge springs from this, as well as the availability of data on all components of the assessment; accident rates, mobility and environment. Neither of the other assessments on the other safety measures manages to produce data on environmental effects, and both provide only minor study contributions for mobility. That being said, it can be argued that measures such as guard rails are not perceived to have any particular effects on the environment, and as such, the topic is deemed unworthy of investigation.

Despite the fact that the book section on guard rails and crash cushions uses almost twice as many studies as the one for grade-separated junctions, the section on grade-separated junctions lists almost twice as many results as the section on guard rails and crash cushions. In regards to amount of discussion on the results, these sections are rather similar. A likely case is that most of the studies used provided general findings, and details deemed by the author to be irrelevant for the data collection.

It has been found that the assessments of guard rails and crash cushions, and grade-separated junctions are based on relatively equal strength of knowledge, verdict medium. This is similar to the assessment of cost-benefit for the measures, where guard rails and crash cushions are evaluated at a benefit-cost ratio of 2, and grade-separated junctions have a benefit-cost ratio of 2.2. Grade-separated junctions do perform better form a cost-benefit perspective, but the sections on cost and cost-benefit analysis specify that many factors such as junction design, junction type and space required to build one, affect the installation/conversion costs. The book warns the reader that cost estimates are not based on recent projects, and are therefore uncertain. For guard rails and crash cushions, the section on cost-benefit analysis comments that the installation of guard rails along the side of the road is cost-effective for roads that have an AADT of more than 3,000. Roads with lighter traffic have accident rates too low to gain a sufficiently great benefit from the measure, to offset the costs of implementation. It is commented that guard rails are often erected despite of this, due to government regulations (Elvik et al., 2009). Similarly, guard rails as medians on undivided highways are cost-effective if the highway has an AADT of over 5,000. The results of the cost-benefit analyses for the two safety measures are thusly presented with certain caveats, indicating that the extent of traffic situations they are applicable to, is limited. The results are not objective; they must be regarded in light of the analysis context. This is also true for the cost-benefit analysis in the book section on roundabouts, where the measure is deemed cost-effective, "at least at the traffic volumes observed in this sample" (Elvik et al., 2009).

It has been found that the assessment of roundabouts is based on comparatively stronger strength of knowledge, which is why the verdict of strong background knowledge is given. Comparatively speaking, the book section on roundabouts definitely has the most detailed discussion on the use of information from the literature study. Comments are provided for several sources, on both short-comings associated and strengths associated with the studies. This grants the reader of the book section a more nuanced picture of the collected results. The literature study conducted features many relatively recently published studies, and contains a lot fewer publications of advanced age than the sections on grade-separated junctions and guard rails and crash cushions. Roundabouts are given the relatively lowest benefit-cost ratio of 1.8 in *The Handbook of Road Safety Measures* (Elvik et al., 2009), but as the analysis is based on stronger knowledge than the other safety measure assessments, a case could be made for ranking this safety measure higher than the others, particularly since the benefit-cost ratios are so similar for the measures presented in the thesis. Of course, it is ultimately up to the decision-maker to decide how to rank the safety measures. The assessment of background knowledge has however succeeded in its contribution to informed decision-making.

Chapter 4 - Discussion

4.1 - The Handbook of Road Safety Measures as a decision-making basis for prioritization of road safety measures

It would be incorrect to claim that the authors of *The Handbook of Road Safety Measures* (Elvik et al., 2009) provide no insights whatsoever into their interpretations of studies used to derive the cost-benefit analyses. In most cases, some information about strength of knowledge is included in the form of brief comments on results, or vague references to the meta-analysis conducted to summarise study results. This indicates that some thought to knowledge assessment is in fact present, although perhaps not fully realized, as some safety measure sections make little or no mention of the authors' interpretations of the results. It is however interesting that certain safety measures in the book have much more detailed reflections of study results than others, as seen when comparing the book section on guard rails and crash cushions with the book section on roundabouts in section 3.4 of the thesis. It can appear as if the authors only comment on results of literature when they find them somehow lacking or uncertain, further indicating that brief comments on literature means that the authors are certain that the results used are perfectly suitable for their analysis.

4.1.1 - How should the background knowledge be assessed?

The background knowledge assessment performed in section 3.4 of the thesis is very general and based mostly on inference by the comments provided by the authors of *The Handbook of Road Safety Measures* (Elvik et al., 2009). Since it is the task of the authors of the book to interpret and utilize the information in the studies, it is very possible that different results may be obtained from a background knowledge assessment performed by the authors themselves. In sub-section 2.1.4 of the thesis, a list of characteristics regarding the strength of knowledge from a framework presented by (Flage & Aven, 2009) is presented. This list explains that strong knowledge is identified by following aspects:

- The phenomena involved are well understood; the models used are known to give predictions with required accuracy.
- Assumptions made are seen as very reasonable.
- Much reliable data are available.
- There is broad agreement among experts.

Ideally speaking, all information used for the calculations in the cost-benefit analyses in *The Handbook of Road Safety Measures* (Elvik et al., 2009) should be able to be characterized by these bullet points, it is however rarely the case that all sources of information used for an analysis fulfil the criteria set by the list.

The list on qualifiers for strong background knowledge is very general and applicable to almost any type of knowledge, as intended by its creators. In order to assess the strength of knowledge used for the analyses in *The Handbook of Road Safety Measures* (Elvik et al., 2009) using a methodology like that, it would be more useful to discuss more targeted points of the topic in each analysis. Although the assessment of the knowledge used in the analyses of road safety measures can be performed in many different ways, there are always particularly important aspects to focus on. Below are suggestions for such aspects:

- Are the studies recent enough to still be relevant for the ever-changing and evolving traffic scene?
- Do the studies adequately cover the extent of the effects made by the safety measure?
- Are the assumptions made in the studies reasonable?
- For studies that investigate the same safety measure, are the studies performed in such a way that their results are comparable?
- For studies that investigate the same safety measure, is there disagreement or do the studies provide conflicting results?
- Is the resulting information from the studies sufficiently comparable to the problems and objectives that the safety measures are intended to handle?
- Are the methods used in the studies in line with those commonly accepted by the scientific community to produce reliable results?
- Do the studies account for outside factors which may affect the performance of the investigated safety measure?

As the author of this thesis, or any other reader of the book, is not privy to assumptions or simplifications made during the study summation process which results in the tables presented in *The Handbook of Road Safety Measures* (Elvik et al., 2009), proper classification and elaboration on background sources becomes difficult. Assessing another analyst's use of background knowledge used in their analysis is not the simplest task. An outsider is not able to instinctively know how the analyst thinks and processes information. This is why the comparison of the background knowledge used in the safety measure assessments in The Handbook of Road Safety Measures presented in this thesis is performed by inference. The best effect of background knowledge assessment will be achieved when the assessment is performed by the harbourers of the knowledge themselves, as they are the ones who actually collect and utilize it. The work presented in this chapter of the thesis only illustrates the importance of considering the information and assumptions used to create analyses which incorporate expected values, which are influenced by subjective judgements, such as cost-benefit analyses.

4.2 - Road safety work in Norway

It is commonsensical that the assessment of road safety measures must reflect the goals of their implementers, in order to promote the work done to fulfil them. It is plainly stated on their homepage (Statens vegvesen, 2018a) that the NPRA wishes to, eventually, completely eliminate fatalities and severe injuries connected to traffic. The Vision Zero strategy has been implemented in order to guide efforts on road safety in the Norwegian public road industry. This is a goal seen as rational, as it fulfils all criteria for rational goals (see Figure ? in section ?). For contrast, the European Union adopts a more general approach and focuses its attention on safety measures that "are known to be effective in a broad range of situations and across countries" (European Commision, 2019). A commonsensical approach, as the union is comprised of a group of countries with widely varied road architecture, traffic attitude and weather. Effectively covering as much general ground as possible through general policies and regulations is a sensible approach for them. It could be argued that Vision Zero is a poorer fit for the European Union, as managing traffic safety for every country in the European Union is not an approachable task.

There are various analysis methods and perspectives available for creating a basis for informed decision-making regarding safety measures to implement. Two main method categories for project analysis is the economic perspective, which involves monetary concerns weighted against other valued facets, and the safety perspective, which aims to secure lives and manage uncertainty and risk. As discussed in the thesis, since the Norwegian public road industry is thought to have much lower uncertainty associated with its activities when compared to other industries such as the petroleum industry, more weight is given to analysis methods which rely upon expected values for costs and benefits. Cost-benefit analysis is not totally sufficient as a strategy to prioritize road safety measures from a risk perspective, and it could therefore be argued that a more flexible assessment that includes both economic and safety perspectives should be used. The following thesis suggests how this potential joint perspective may be structured, to better suit the assessors' (the NPRA in this case) eventual goal of zero traffic-related deaths and severe injuries.

On the homepage of the Norwegian Public Roads Administration, the following is written about its safety measure implementation policies and goals, translated from Norwegian by the author of this thesis (Statens vegvesen, 2018a):

> *"Since the 1970s, an overall positive reduction in number of fatalities and severely injuries caused by traffic incidents has been recorded. This trend has been observed, despite a steady increase in traffic volume. Amongst important contributors to this positive development, targeted efforts by the government, organizations, various interested parties, vehicle producers and the road users themselves, are cited.*

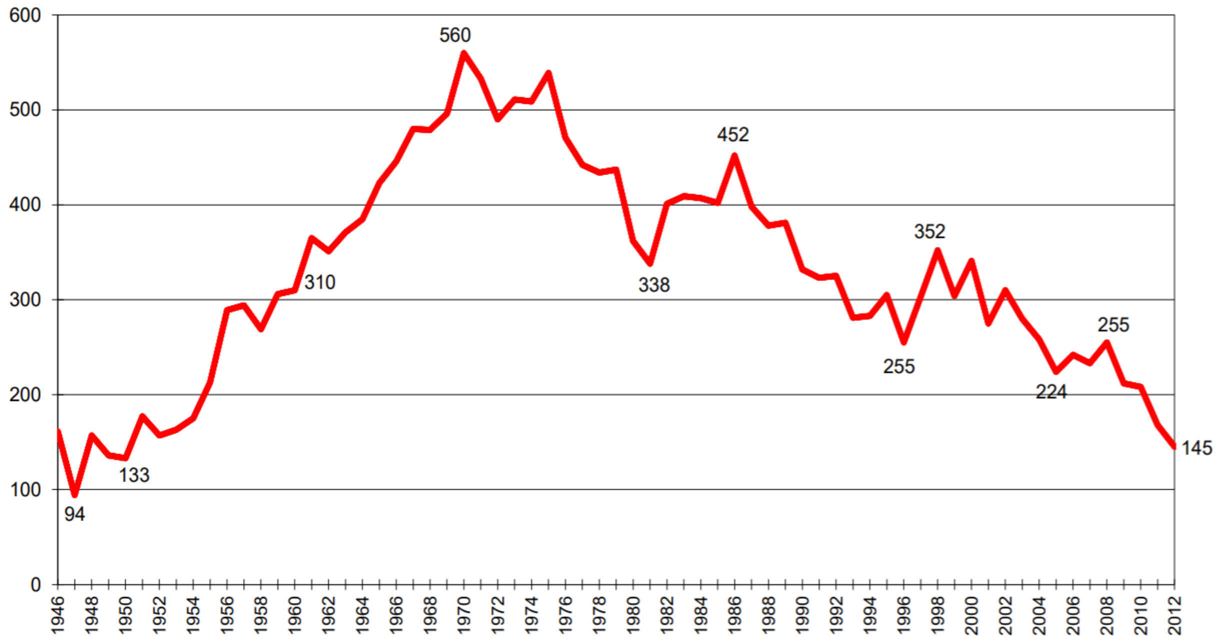


Figure 3: Graph of traffic-related fatalities in the period 1946-2012 (Statens vegvesen, 2018a)

> *And yet, Norwegian roads saw 145 fatalities and 699 severe injuries in 2012. We are still quite far away from Vision Zero, and must therefore continue our efforts to reduce the number of fatalities and severe injuries in traffic. In order to ensure the success of our work, we need basic analyses, sound methodology, concrete goals and prioritization of road safety measures."*

It can be surmised from this that the NRPA are aware of the challenges they are faced with, and wish only to improve their work of improving safety on roads. Norwegian public road work is characterized as a "low uncertainty" industry, when comparing to other industries such as the petroleum industry. This relaxed attitude towards presumed low uncertainty levels has prompted the government entity in charge of road safety to give, perhaps, undue weight to monetary considerations when deciding how to approach a safety problem on Norwegian roads. Present decision-making criteria for prioritizing between implementation of various safety measures on roads relies heavily on cost-benefit analyses (Elvik, 2001a). As one of the main challenges of using cost-benefit analyses as a decision-making basis, as is currently the practise in the NPRA, is that the method relies on expected values for costs and benefits. Due to the assumed low uncertainty associated with the public roads industry, it is considered useful to give more weight to the economic side of the problem. But what about the uncertainty connected to use of expected values?

In a road safety measure impact assessment conducted as a part of transport planning for the period 2010-2019 (Elvik, 2007), serious doubt regarding the feasibility of a rather ambitious traffic safety goal was raised. As a part of the Vision Zero strategy which dictates public road safety work in Norway, this goal was to reduce traffic accident fatalities by 50% by the year 2020. In the report, 4 policy options are developed based on 39 safety measures assessed to be cost-effective. These policy options are assessed exhaustively with respect to how much implementation of each of them possibly could contribute to reducing road accident fatalities. The assessment concludes with none of the options considered being able to produce the wanted goal of a 50% fatality reduction. The author of the report goes on to conclude that the real-world prospects of improving road safety in Norway to such an extent by 2020 are even bleaker than the idealized policy options assessed in the report suggest. In summation, idealized safety measure priority policies based on cost-benefit analyses are assessed to be insufficient for the overall goal of the decision-makers. As investigated and proven in the report (Elvik, 2007), policies created with such a restricted economic perspective show bleak predictions of even achieving the step-goals laid out by the government.

4.3 - Cost-benefit analysis of road safety measures - a blind alley?

The assessment of three safety measures in chapter 4 of the thesis shows that safety measures which are deemed equal in impact by cost-benefit analyses, may in fact vary greatly in actual effect. When no consideration is granted to which assumptions and presuppositions lay the groundwork for the knowledge upon which the analyses are based, the results of the analyses become less consistent and to a certain extent incomparable. This does not mean that the thesis aims to advice against the use of cost-benefit analyses in comparably low-uncertainty industries such as the Norwegian public road industry. It merely seeks to advice analysts to conduct deeper assessments of the knowledge used to conduct them. The thesis uses the contents of *The Handbook of Road Safety Measures* (Elvik et al., 2009) as an example to highlight this, due in part to the solid structure of the book, and in part because it serves as a brilliant illustration of this very aspect; large lists of sources and result summaries in tables of figures for various accident rate reducing effects are provided for each safety measure, but the studies' contribution to the background knowledge must be inferred by the reader of the book. Comments are sometimes provided on certain studies which are deemed particularly corroborative with other studies, or particularly lacking in some way or other, but what effect such studies has on the overall analysis is not discussed. Based on these observations, the thesis urges the authors of the book to provide more information about how knowledge is used in their analyses. This will increase reader confidence in the presented results, as well as allow for better informed decision-making.

Chapter 5 - Final words and conclusion

The work conducted to complete this thesis was related to the implied reliance on cost-benefit analyses in the NPRA when, for example, prioritizing between road safety measures to implement. It was discovered that where cost-benefit analyses gave similar values for different measures, thus providing little guidance as to how to prioritize between them, a brief assessment of the background knowledge proved useful. For the examples used in the thesis, it was found that the safety measure judged to be the least cost-effective of the three also had the most effort granted to discussion on the sources used to assess its effects. The knowledge for this safety measure was given a verdict of strong knowledge, while the others were both given verdicts of medium knowledge. This result implies that different decisions may be made depending on how the decision-maker chooses to value expected values and uncertainty: is a slightly higher benefit-cost ratio with calculated based on medium knowledge better than a slightly lower benefit-cost ratio calculated with stronger knowledge? With the addition of knowledge assessment, the analyses presented in The Handbook of Road Safety Measures (Elvik et al., 2009) were able to provide better decision-making support.

In regards to ongoing safety work connected to presented work from this thesis, it is suggested that if a third edition of *The Handbook of Road Safety Measures* should be published, then perhaps a short summation of background knowledge assessment could be included, as partially demonstrated and discussed in this thesis. This will increase confidence in the assessment process as well as help both the analyst and the reader further understand the effectiveness of the measure, beyond a simple relation to how much it costs to implement. Some considerations on how to assess the background knowledge used in the cost-benefit analyses in future editions of *The Handbook of Road Safety Measures* were provided. These were based primarily on the general knowledge assessment framework by (Flage & Aven, 2009).

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